Does breathing disturb arm to leg coordination in butterfly

Does Breathing Disturb Coordination in Butterfly?

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- motor control
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Abstract

This study quantified the effects of breathing compared to non-breathing and "race pace" on arm to leg coordination in the butterfly stroke. Twelve elite male swimmers swam at four paces: 400 m, 200 m, 100 m and 50 m. The arm and leg stroke phases were identified by video analysis to calculate the total time gap (TTG), which is the sum of T1 (hands' entry in the water/high point of first kick), T2 (beginning of the hands' backward movement/low point of first kick), T3 (hands' arrival in a vertical plane to the shoulders/high point of second kick) and T4 (hands' release from the water/low point of second kick). Two strokes with breathing were compared to two strokes with breath-holding. The TTG was greater with breathing (23.3% *vs.* 19%), showing less propulsive continuity between arm and leg actions ($p < 0.05$). This was due to the shorter downward leg kick and longer arm catch and upward leg kick that led to longer glide time. Conversely, breathing leads to greater coupling between the hand exit and the end of leg propulsion, which was due to a shorter arm push phase to facilitate the head exit to breathe.

Introduction

The greatest intra-cyclic velocity fluctuations in swimming (45–50% of the mean velocity) were found in butterfly and breaststroke [7] and were related to high energy cost i.e. to less efficient swimming [2]. Since frontal breathing may disturb arm to leg coordination and increase the velocity fluctuations [9], controlling the ratio of breaths to arm strokes could help to ensure a high degree of propulsive continuity and a streamlined body position. Usually, swimmers use one breath for every two arm strokes or they breathe for every stroke. In fact, several breathing patterns (breath-holding, frontal breathing, lateral breathing) with different ratios of breaths to arm strokes have at times been adopted, yet there is little evidence of the best compromise between oxygen supply, the disturbance in propulsive continuity, instantaneous velocity fluctuations and variations in active drag.

The findings to date nevertheless indicate that the stroke phase organisation should be balanced as regards breathing and breath-holding. Several recent studies in front crawl emphasised the effect of breathing on arm stroke phases and inter-arm coordination [12, 13, 22] and provided evidence that breathing disturbs the propulsive continuity and causes catch-up coordination. Cardelli et al. [5] studied the durations of exhalation, inhalation and inhalatory apnea and found longer inhalations in non-expert swimmers at high speed, indicating that the lack of breathing may affect stroke phase organisation and arm coordination. In fact, for less experienced swimmers, it appeared that propulsive continuity was lower on the breathing side than on the non-breathing side [12]. Although a discontinuity between the propulsive phases of the two arms was noted to occur on the breathing side due to the breathing action, breathing laterality due to a learned unilateral breathing pattern also explained the asymmetry of arm coordination in front crawl [22].

Maglischo [14] advised butterfly swimmers to use two leg kicks for one arm stroke. During the outsweep of the arm stroke, the head, shoulders and trunk should rise towards the surface of the water as the swimmer slowly exhales and should then break the surface during the transition from insweep to upsweep and the end of exhalation [14]. Inhalation should occur during the upsweep and the first half of the arm recovery, with the head returning to the water during the second

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half of the arm recovery [14]. Few studies have analysed the effect of breathing on propulsion, kinematics, instantaneous velocity fluctuations or coordination in butterfly [1,3,4,9]. Barbosa et al. [3] analysed the difference between hip and centre of mass as regards kinematic variables (vertical amplitude of displacement, intra-cycle variation of the horizontal velocity and acceleration) when different breathing patterns were used (frontal, lateral and restrained inhalation), but without emphasising the effect of the breathing pattern. Hahn and Krug [9] observed a decrease in velocity with breathing due to a body angle 10° greater during inhalation and a longer arm recovery. This longer recovery caused a change in arm to leg coordination, because the downward leg kick occurred earlier in relation to the underwater movement of the arms during the next stroke [9]. Alves et al. [1] studied the effect of frontal breathing on kinematics; notably they noted greater trunk inclination with frontal breathing as compared to breath-holding for the lesser experienced swimmers [1]. A lower trunk inclination occurred during lateral breathing, as compared to frontal breathing but a rotation around the longitudinal axis of the whole body was created [4]. All these studies provided interesting kinematic information about the effects of breathing, but the possible disturbance of arm to leg coordination was not examined.

Chollet et al. [6], Seifert et al. [21] demonstrated the need for high coupling between the arms and legs in butterfly. Using four discrete time gaps (T1, T2, T3, T4) to assess the coordination, they particularly pointed out that elite swimmers show low propulsive discontinuities (the relative durations of T1, T3 and T4 were <4% of the duration of a complete stroke) and a relatively short glide with the arms extended forward (measured by T2 which was <17% of the duration of a complete stroke). Unlike in front crawl, however, no published study has ever investigated how breathing affects butterfly coordination. Therefore, the aim of this study was to compare the effects of breathing or not breathing, and "race pace", on arm to leg coordination in the butterfly stroke. With respect to breathing it was hypothesised that changes in arm to leg coordination would occur to facilitate breathing, which would in turn increase the propulsive discontinuities and decrease the propulsive phases.

Material and Methods

Subjects

Twelve elite male swimmers, either national finalists or internationally-ranked (mean age: 20.3±3.9 years; mean height: 180.9±4.9 cm; mean arm span: 189.8±4 cm; mean mass: 73±7.8 kg) provided informed written consent to participate in the study which was approved by the university ethics committee. This study has been conducted in accordance with recognised ethical standards and national/international laws reported by Hariss and Atkinson [10]. Their best performance for a 100 m butterfly corresponded to 56.4±1.3 s in a 50 m pool and was expressed in percentage of the world record W.R.: 50.40 s; thus, % W.R. = $\text{Time}_{\text{W.R.}}/\text{Time}_{\text{subject}} * 100 = 89.4 \pm 2.5\%$.

Swim trials

In a 25 m pool, the swimmers performed four butterfly trials at successively increasing paces corresponding to a specific race or training distance: the 400 m, the 200 m, the 100 m and the 50 m, with a 4 min rest between trials. The trials consisted of swimming at the imposed pace only for a distance of 25 m in order 1) to prevent fatigue effects and 2) knowing that active drag varies with velocity square, to impose different levels of active drag that enables to examine how the environmental constraint (active drag) affected the motor control adaptations. After each trial, all swimmers were informed of their performance time, which was expected to be within ±2.5% of the targeted race velocity [6,21,23]. If this was not the case, the subject repeated the trial. The swimmers were asked to breathe frontally alternating one breathing stroke with one breath-holding stroke.

Video analysis

An aerial lateral video camera was superposed on an underwater lateral video camera (50 Hz, Sony compact FCB-EX10L). Both had higher shutter speed (1/1 000 s) and were fixed on the same trolley. The trolley was pulled along the side of the pool by an operator at the same velocity as the swimmers, with each subject's head being the mark followed by the operator to control parallax. The two cameras were connected to a double-entry audio-visual mixer, a video timer, a video recorder and a monitoring screen to genlock and mix the lateral underwater and aerial views on the same screen. A third camera (50 Hz, Sony compact FCB-EX10L) videotaped the swimmers from a frontal underwater view and was genlocked and mixed with the underwater lateral view on another screen. From this video device, three operators analysed the key points determining the starts and ends of the arm and leg stroke phases. The precision of this technique is 0.02 s and the operators used a blind technique. The three analyses were compared only when each operator had completed his own analysis. When the difference between the three analyses did not exceed an error of 0.04 s, the mean was accepted to validate the key point of each phase. When the error exceeded 0.04 s, the three operators together proceeded to a new assessment of the phase key points.

Last, a fourth camera (50 Hz, Panasonic NV-MS1 HQ S-VHS), genlocked and mixed with the lateral underwater view for time synchronisation, videotaped all trials with a profile view from above the pool. This camera allowed us to measure the time it took for each swimmer to cover a distance of 12.5 m (from 10 m to 22.5 m) for the calculation of the average velocity and the stroke rate. Two plots delimited the 10 m and 22.5 m points on the right and left sides of the pool. When the head of the swimmer reached the rope line at 10 m, time was recorded until the head reached the line at 22.5 m. The duration of one complete stroke was from the left hand entry at stroke 1 to the left hand entry at stroke 2 and stroke rate was obtained by counting the requisite number of video frames for the four strokes of the 12.5 m. Using the average velocity and the stroke rate, the stroke length could be calculated: stroke length = (velocity/stroke rate)*60.

Arm and leg stroke phases

As shown in ○ **Fig. 1**, the key points of the arm were used to determine the starts and ends of the four phases that compose an arm stroke [6,21]:

1) Entry and catch of the hands in the water, which corresponds to the time between the entry of the hands into the water and the beginning of their backward movement; *2) Pull phase*, which corresponds to the time between the beginning of the backward movement of the hands and their entry into the plane vertical to the shoulders; *3) Push phase*, which corresponds to the time between the positioning of the hands below the shoulders and their exit from the water. The pull and the push phases corre-

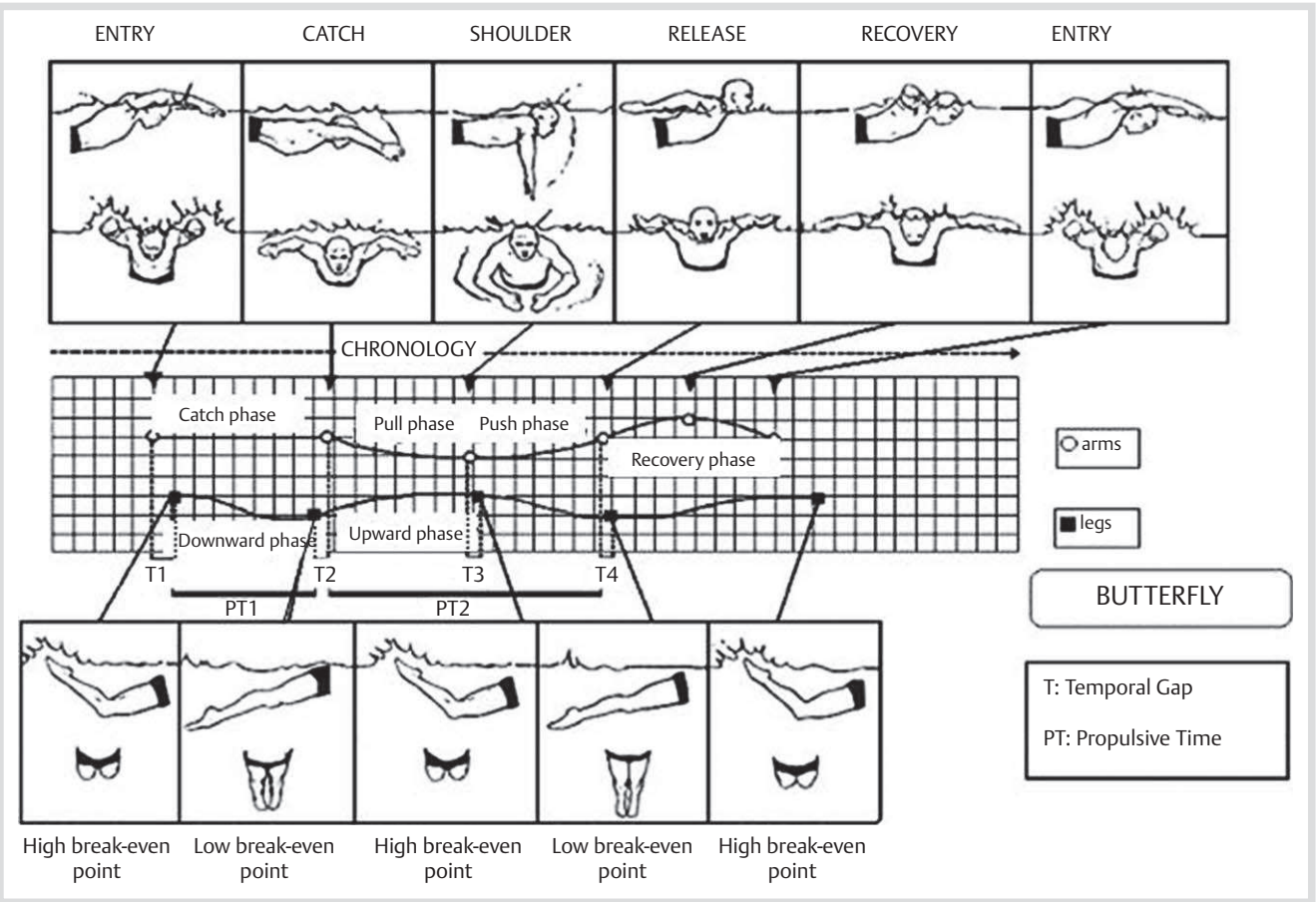

Fig. 1 Synchronised structure of the arm and leg for butterfly swimming [6]: T1: entry of the hands in the water/high break-even point of the 1st kick; T2: beginning of the hands' backward movement/low break-even point of the 1st kick; T3: hands' arrival in a vertical plane to the shoulders/high break-even point of the 2nd kick; T4: hands' release from the water/low break-even point of the 2nd kick.

spond to the arm propulsive time; and *4) Recovery phase*, which corresponds to the time between the exit of the hands from the water and their following entry into the water.

The duration of each phase was measured for each stroke with a precision of 0.02 s and was expressed as a percentage of the duration of a complete arm stroke.

As shown in ○ **Fig. 1**, the key points of the legs were used to determine the starts and ends of the four phases that compose a leg stroke [6,21]. One leg stroke corresponded to two leg kicks and one leg kick comprised one downward phase and one upward phase. Only swimmers with two leg kicks for one arm stroke were studied. The four phases were:

1) Downward phase 1, which corresponds to the time between the high and low break-even points of the feet during the first kick; *2) Upward phase 1*, which corresponds to the time between the low and high break-even points of the feet during the first kick; *3) Downward phase 2*, which corresponds to the time between the high and low break-even points of the feet during the second kick; and *4) Upward phase 2*, which corresponds to the time between the low and high break-even points of the feet during the second kick.

The duration of each phase was measured for each stroke with a precision of 0.02 s and was expressed as a percentage of the duration of a complete leg stroke.

Arm to leg coordination

Four time gaps were identified [6,21] (○ **Fig. 1**): *T1* is the time difference between the start of the arms' catch phase and the start of the legs' downward phase of the first leg kick; *T2* is the time difference between the start of the arms' pull phase and the start of the legs' upward phase of the first leg kick; *T3* is the time difference between the start of the arms' push phase and the start of the legs' downward phase of the second leg kick; and *T4* is the time difference between the start of the arms' recovery and the start of the legs' upward phase of the second leg kick. The time gap was <0% when the leg key point occurred before the arm key point and, logically, the time gap was >0% when the leg key point occurred after the arm key point. The *total time gap* (TTG) was defined as the sum of the absolute values of T1, T2, T3 and T4, and was used to assess the effectiveness of the global arm to leg coordination. In all trials, the time gaps and TTG were expressed as the percentage of a complete stroke.

Effect of breathing

For each "race pace", one breathing stroke is alternated with one breath-holding stroke and four consecutive strokes taken in the 12.5 m central part of the pool are analysed. Therefore there are two alternations between one breathing stroke and one breath-holding stroke.

Statistical analysis

A normal distribution (Ryan-Joiner test) and the homogeneity of variance (Bartlett test) were checked for each variable and allowed parametric statistics. One-way repeated measures ANOVA (pace) with Tukey pairwise post-hoc tests were used to test for differences between the four paces for each of the stroking parameters (velocity, stroke rate, stroke length). Two-way repeated measures ANOVA (breathing * pace) with Tukey pairwise post-hoc tests were used to analyse coordinative parameters (TTG, T1, T2, T3, T4) and stroke phases. For the coordinative parameters, the between-factor effect size was calculated from η^2 as the difference between the sum of squares between factor and the total sum of squares. The effect size explained the variance, i.e. indicated the amount of association between breathing patterns and race paces that was due to breathing or breath-holding and to increase in race pace. $\eta^2 = 0.2$ is small, $\eta^2 = 0.5$ is moderate, $\eta^2 > 0.8$ is large differences. All tests were performed with Minitab 14.10 (Minitab Inc., 2003), with a level of significance set at $p < 0.05$.

Results

Velocity, stroke rate and stroke length were analysed only to characterise each "race pace", i.e. to link the changes in coordination (when breathing or breath-holding) with a performance. Velocity and stroke rate increased while stroke length decreased when race pace increased (**Table 1**).

Stroke phases and coordination of arms and legs

Pace effect

When pace increased, the total time gap (TTG) decreased, indicating higher continuity between the arm and leg key points; this was due to decreases in T1 and T2 (**Table 2**). The calculation of the effect size showed moderate to large values suggesting that the "race pace" significantly influenced the change of the coordinative parameters (**Table 2**).

The changes in TTG with the increase from the 400 m to the 50 m pace were related to an increase in the relative durations of the arm pull from 21 ± 4.3% to 25.4 ± 5.6% ($F_{3,184}$ = 10.55, $p < 0.05$), the arm recovery from 23.2 ± 2.9% to 27.5 ± 2.9% ($F_{3,184}$ = 19.11, $p < 0.05$), and the first downward leg kick from 15.2 ± 3.2% to 17.6 ± 3% ($F_{3,184}$ = 6.23, $p < 0.05$), and a decrease in the relative durations of the arm entry and catch from 34.9 ± 6.7% to 24.8 ± 6.4% ($F_{3,184}$ = 21.87, $p < 0.05$) and the first upward leg kick from 33.6 ± 5.8% to 30.2 ± 4.6% ($F_{3,184}$ = 6.25, $p < 0.05$).

Breathing effect

On the mean of the four paces, TTG was greater with breathing than with breath-holding, revealing that breathing led to propulsive discontinuities, particularly evidenced by a greater T2, which measured the glide with the arms extended forward while the legs were at their low break point (**Table 3**). The calculation of the effect size showed moderate to large values suggesting that breathing significantly influenced the change of the coordinative parameters (**Table 3**).

The. longer glide in the breathing condition was due to a change in the arm and leg stroke phases: 1) a longer arm catch phase (30.7 ± 8.5% *vs.* 28 ± 6.5%) ($F_{1,184}$ = 4.3, $p < 0.05$), 2) a shorter first downward kick of legs (15.8 ± 3.4% *vs.* 17.3 ± 2.3%) ($F_{1,184}$ = 10.57, $p < 0.05$), and 3) a longer first upward kick of legs (32 ± 6% *vs.* 29.7 ± 3.8%) ($F_{1,184}$ = 8.02, $p < 0.05$).

Conversely, breathing led to a smaller T4 (**Table 3**), which indicated better synchronisation between the hand exit and the low break point of the legs. In fact, when the swimmer breathed, the hand exit occurred closer to the end of the leg propulsion because the push phase of the arms was shorter (20.2 ± 3.6% *vs.* 22.8 ± 3%) ($F_{1,184}$ = 25.96, $p < 0.05$).

Interaction between pace and breathing

The post-hoc Tukey tests showed smaller T4 for the sprint paces (100 m and 50 m) than for the slow paces (400 m and 200 m) in the breathing condition ($F_{3,184}$ = 3.1, $p < 0.05$). (**Fig. 2**).

Table 1 Changes in stroking parameters with increases in pace.

Paces	Velocity ($m.s^{-1}$)		Stroke Rate ($stroke.min^{-1}$)		Stroke Length ($m.stroke^{-1}$)	
	Mean	SD	Mean	SD	Mean	SD
400 m	1.45	0.1	38.9	4.2	2.25	0.25
200 m	1.56 **a**	0.08	43.2 **a**	3.5	2.18	0.18
100 m	1.68 **a c**	0.08	49.8 **a c**	3.1	2.03 **c**	0.14
50 m	1.74 **a b c**	0.08	53.9 **a b c**	3.3	1.93 **b c**	0.12
statistics	$F_{3,44}$ = 24.7		$F_{3,44}$ = 42.23		$F_{3,44}$ = 7.5	

a: significant difference with preceding pace, **b**: with the 200 m, **c**: with the 400 m, $p < 0.05$; SD: standard deviation

Table 2 Changes in coordinative parameters with increases in pace.

Paces	T1 (%)		T2 (%)		T3 (%)		T4 (%)		TTG (%)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
400 m	3.8	3.2	−16.3	8.5	−3.2	4.9	−1.7	2.4	27.9	11.1
200 m	3.3 **a**	3.0	−11.3	7.2	−3.9	4.4	−1.9	2.9	22.7 **a**	9.6
100 m	1.7 **a c**	3.4	−7.6 **c**	5.7	−3.5	3.6	−1.6	3.8	18.1 **a c**	7.2
50 m	1.1 **b c**	5.3	−7.0 **b c**	5.1	−2.3	3.5	−2.8	3.8	17.0 **b c**	4.9
statistics	$F_{3,184}$ = 4.97		$F_{3,184}$ = 18.51						$F_{3,184}$ = 15.58	
effect size	$\eta 2$ = 0.37		η^2 = 0.75						η^2 = 0.69	

a: significant difference with preceding pace, **b**: with the 200 m, **c**: with the 400 m, $p < 0.05$; SD: standard deviation; TTG: total time gap

Table 3 Changes in coordinative parameters with breathing condition.

Breathing	T1 (%)		T2 (%)		T3 (%)		T4 (%)		TTG (%)	
Condition	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
with breathing	2.7	4.5	−12.2	3.9	−3.6	4.2	−1.1	2.8	23.3	8.7
breath-holding	2.2	3.5	−9.1*	3.7	−2.9	4.0	−2.8 *	3.4	19.7*	7.8
statistics			$F_{1,184}=5.1$				$F_{1,184}=13.37$		$F_{1,184}=4.1$	
effect size			$\eta^2=0.41$				$\eta^2=0.66$		$\eta^2=0.35$	

*: significant difference with preceding breathing condition, $p<0.05$; SD: standard deviation; TTG: total time gap

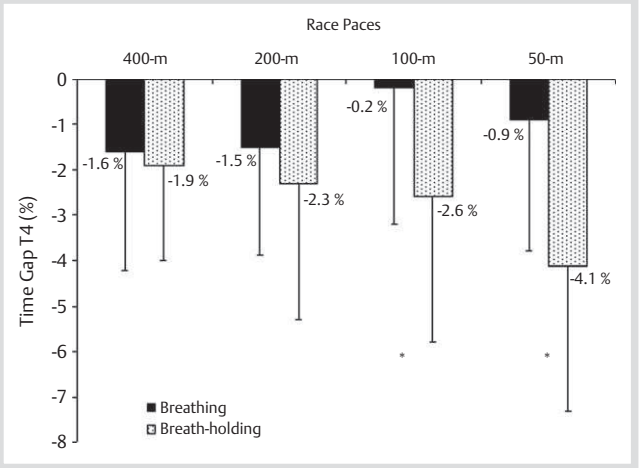

Fig. 2 Differences in T4 as regards the interaction of pace and breathing effects: *: significant difference between breathing and breath-holding at $p<0.05$.

Discussion

Pace effect

According to previous studies [6,21,23], the increase in pace led to a decrease of the TTG values; in other words, it means a higher synchronisation between the key points defining the beginning and the end of the arms and legs stroke phases and an increase in the propulsive continuity. Swimming is a cyclic task (in butterfly, arms and legs oscillate with a 1:1 or 1:2 frequency ratio) as walking, running and the bimanual coordination task in which it was noted that an increase in frequency and/or in velocity leads to higher inter-limb coupling (i.e. transition from an anti-phase to an in-phase mode of muscle contraction) [11]. In our study, the higher inter-limb coupling and arms-legs propulsive continuity resulted from a decrease in the relative duration of the glide and catch phase of the arms while the legs were at their high (measured by T1) and low (measured by T2) key points. In fact, in breaststroke, the arms have a "reserve capacity" of time to move faster [15], which explains the glide variation. Similarly, in butterfly, the catch phase of the arms was also the only time when the arms had a "reserve of capacity" because later in the cycle (i.e. at T3 and T4), perfect synchronisation was required. Indeed, because the hands attained their deepest path at the beginning of the push phase, the beginning of the downward leg kick had to correspond with the beginning of the arm push phase (i.e. a small T3) to provide a superposition of two propulsive phases and the highest acceleration of the stroke [15,16]. The time gap T4 had also a low value; thus, the end of the downward leg kick facilitates the exit of the hands [14]. Finally, the higher the arms-legs stroke phase coordination is, the better the propulsive efficiency should be.

Breathing effect

Breathing caused propulsive discontinuity (greater TTG) that was related to a longer glide time with the arms extended forward (measured by T2, see **Fig. 3**) in order to catch water just before breathing. A longer arm catch phase initiates the head and shoulder elevation and the trunk inclination to inhale. This was in accordance with previous studies in front crawl, which suggested that breathing leads to time lag between the propulsion of the two arms and causes catch-up coordination [12,13,22]. As in front crawl, breathing modified the butterfly stroke phase organisation because during the arm catch phase, the head, shoulders and trunk rose towards the surface; thus the swimmers exhaled before breaking the surface to inhale [14]. Sanders et al. [19] noted that the swimmer's head initiates a wave action, with shoulder, hip, knee and ankle progressively contributing to the kick. They showed the important role played by the head in this wave action and consequently the impact of the head rising to breathe in this mechanism. Alves et al. [1], Hahn and Krug [9] showed an increase of 10° in trunk inclination relative to the horizontal axis during inhalation in competitive swimmers.

Moreover, our elite swimmers showed a shorter downward leg kick and a longer upward leg kick when breathing (**Fig. 3**). According to Alves et al. [1] and Hahn and Krug [9], the shorter relative duration of the downward leg kick could correspond to an acceleration of the leg to prepare the trunk inclination to inhale, in association with the arm glide. Indeed, a deeper kick was observed by Alves et al. [1] when swimmers breathed, while Hahn and Krug [9], who used a tensogram, noted a weaker first kick after breathing and consequently a stronger kick before breathing. In fact, Sanders et al. [19] hypothesised that the vertical movements of the head and shoulders may be beneficial because they initiate a backward body wave, which enables the force from the first downward leg kick to accelerate the swimmers rapidly forward. More precisely, a body wave travels back from head to feet (called "reserve body wave" [14]) and follows the first downward leg kick, thereby improving the forward acceleration received by this leg kick.

Breathing was associated with: 1) a decrease in the arm push phase and 2) a higher synchronisation between the hand exit and the low break-point of the legs (measured by T4, see **Fig. 3**). This arm to leg coordination facilitated the elevation of the head, shoulders and trunk above the surface for inhalation but did not warrant better propulsion. Indeed, a decrease in the relative duration of the arm propulsion (push phase) was observed when breathing. To minimize the decrease in the push phase and the increase in active drag, the head should stay in a normal position with the eyes focused down and forward [14].

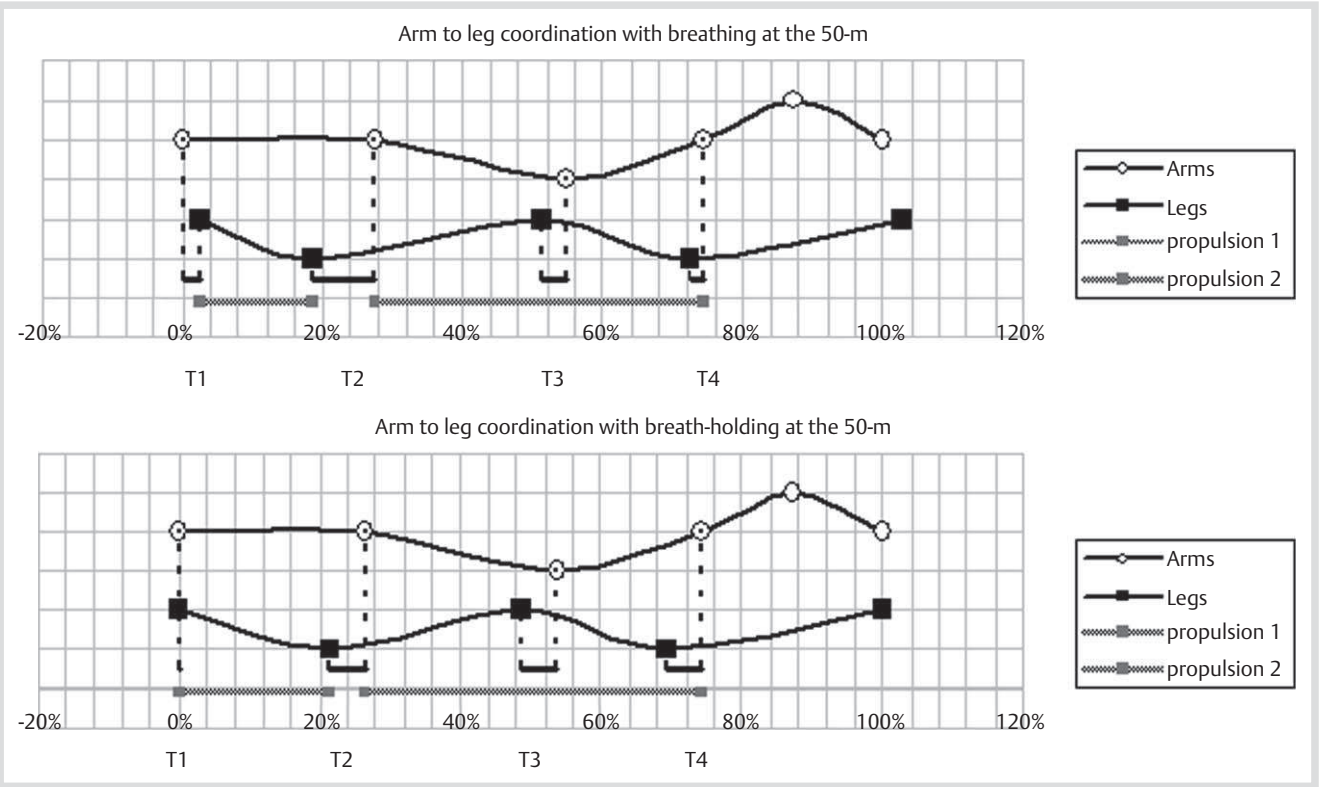

Fig. 3 Example of arm to leg coordination in relation to the two breathing conditions.

Conversely, it was hypothesised that a late exit of the hand in relation to the end of the downward leg kick (corresponding to high value of T4) would lead to lifting the head up and back because the arm recovery would be out-of-phase.

Finally, the coupling of the hand exit with the low break-point of the legs was found to increase from the 400 m to the 50 m pace, T4 being close to 0% at the 50 m pace (▶ **Fig. 2**). Many researchers have shown that the degree of coordination between breathing and additional movements (tracking movements, walking, running, cycling) increases when stride frequency, velocity and workload increase [8,18,20]. In these studies, the degree of coordination was quantified as the percentage of breaths starting during the starting phase of the voluntary act. For example, the increase in workload from 55 to 95% of VO_{2max} leads to an increase in coordination between the beginning of breathing and the beginning of leg movement in cycling [20]. Even if a different method was used in our study, several elements of conclusion are similar, including the observations that when an imposed constraint is increased (stride frequency, velocity, workload, race pace), breathing contributes to improve the interlimb coordination by a better coupling between breathing and the voluntary act, and that this improved coordination nevertheless does not improve propulsion. Indeed, unlike the other activities in which breathing is free to vary, breathing in butterfly swimming is constrained between tight timelines relative to the other body motions because the head is not continuously above the water.

On the other hand, the improved coordination during breathing disturbed the motor organisation in the breath-holding condition, because T4 switched from −1.9% at the 400 m to −4.1% at the 50 m (▶ **Fig. 2**). This change reveals that the effort made to facilitate inhalation had a repercussion on the following stroke; notably, the push phase finished after the downward leg kick, and this was more pronounced at the 50 m. Indeed, Hahn and Krug [9] suggested that elevating the head out of the water to breathe requires an "additional control of movement resulting in a decrease in velocity".

Conclusion

On the mean of the four paces, the TTG was greater with breathing, showing less propulsive continuity between arm and leg actions. This was due to the shorter propulsive phase (downward leg kick) and longer non-propulsive phases (arm catch and upward leg kick) that led to longer glide time (measured by T2). Conversely, breathing leads to greater coupling between the hand exit and the end of leg propulsion (measured by T4), which was due to a shorter arm push phase to facilitate the head exit to breathe.

Although the time gaps showed small values (<4% for T1, T3, T4 and <17% for T2) in both breathing conditions, confirming the high degree of coordination in the elite swimmers, breathing appeared to be a significant constraint that coaches should monitor in training.

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